Fermi meets Jansky – AGN at Radio and Gamma-Rays
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Young radio sources: a radio-gamma perspective

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Abstract. The evolutionary stage of a powerful radio source originated by an AGN is related to its linear size. In this context, compact symmetric objects (CSOs), which are powerful and intrinsically small ($<$ 1 kpc) radio sources with a convex synchrotron radio spectrum that peaks around the GHz regime, should represent a young stage in the individual radio source life. Their radio jets expand within the dense and inhomogeneous interstellar medium of the host galaxy, which may influence the source growth. The radio emission is expected to evolve as a consequence of adiabatic expansion and radiative and inverse Compton losses. The role played by the different mechanisms in the radio and gamma regimes is discussed.

1. Introduction

Powerful ($L_{1.4\mathrm{GHz}} > 10^{25}$ W/Hz) and intrinsically compact (linear size LS $<$ 1-20 kpc) extragalactic radio sources are considered to represent an early stage in the individual radio source evolution. Their main characteristic is the rising synchrotron radio spectrum which turns over at frequencies from a few hundred MHz up to the GHz regime. The mechanism responsible for the spectral peak is the synchrotron self-absorption (SSA; Snellen et al. 2000), although an additional contribution from free-free absorption (FFA) is present in the most compact objects (Orienti & Dallacasa 2008, Kameno et al. 2000).
When imaged with the high spatial resolution provided by radio interferometers, these objects resemble a scaled-down version of the classical edge-brightened FR II radio galaxies (Fanaroff & Riley 1974). Given their compact and two-sided structures, Wilkinson et al. (1994) termed these sources "Compact Symmetric Objects" (CSO) and suggested a possible evolutionary connection with the larger radio galaxies. Conclusive evidence of the genuine *youth* of this class of objects came from the determination of both kinematic (Polatidis & Conway 2003) and radiative (Murgia 2003, Murgia et al. 1999) ages, which resulted to be in the range of 10^3 - 10^5 years.
Several studies of samples of compact radio sources (O'Dea & Baum 1997) show an anti-correlation between the peak frequency and the linear size: the higher the peak frequency $\nu_{\rm p}$, the smaller the source is. This anti-correlation agrees well with an evolutionary scenario where the peak, caused by SSA, moves to lower frequencies as the source adiabatically expands. In this context we can draw an evolutionary path linking the different stages of the source evolution: the smaller sources (LS $<$ 1 - 50 pc), with $\nu_{\rm p}$ above a few GHz and known as high frequency peakers (HFP), will evolve into the GHz-peaked spectrum (GPS) sources, with LS $\sim$ 1 kpc and $\nu_{\rm p} \sim$ 1 GHz, which will become compact steep spectrum (CSS) objects (LS $\sim$ 1 - 20 kpc, and $\nu \sim$ 100 MHz), i.e. the progenitors of FRIIs.
Several evolutionary models (i.e Fanti et al. 1995, Kaiser & Alexander 1997) have been developed to describe the various steps of the source growth. Given the compact sizes, these objects entirely reside within the host galaxy, enshrouded by the dense and inhomogeneous interstellar medium (ISM), where jet-cloud interaction may play a role on the source growth (Jeyakumar 2009).
In this contribution we describe the role played by the various mechanisms on the source evolution, such as adiabatic expansion, energy losses, and their effects on the source spectrum, in particular in the radio and gamma regimes.

Throughout this paper, we assume $H_0 = 71$ km s^{-1} Mpc^{-1}, $\Omega_{\rm M} = 0.27$, $\Omega_\Lambda = 0.73$, in a flat Universe. The spectral index is defined as $S(\nu) \propto \nu^{-\alpha}$.

2. Physical properties

The knowledge of the magnetic field has crucial implication in the determination of the radio source evolution. The models developed so far consider that the radio sources are in minimum energy condition, which corresponds to equipartition between the particle energy and the magnetic field (Pacholczyk 1970). However, there is no *a-priori* reason why a radio source must be in equipartition.
A direct way to measure the magnetic field is based on observational parameters. In fact, in the case the spectral peak is produced by SSA, the magnetic field H can be computed from peak frequency $\nu_{\rm p}$, peak flux density

$S_{\rm p}$, and angular size θ by the relationship (Kellermann & Paulinity-Toth 1981):

$$H \sim f(\alpha)\theta^4 \nu_{\rm p}^5 S_{\rm p}^{-2} (1+{\rm z})^{-1} \qquad (1)$$

where $f(\alpha)$ is a function weakly dependent on the spectral index (f_α=8 for α=0.5), and z is the redshift. The region considered in Eq. 1 is assumed to be homogeneous and deviations from this assumption introduce uncertainties. Studies of a few CSS carried out at low frequencies (i.e. close to their peak frequency) were subjected to substantial uncertainties on the component size. The high spatial resolution and the frequency coverage of the VLBA match well the requirements for a proper study of the most compact HFP sources, whose spectrum is reasonably fitted by self-absorbed synchrotron emission from a homogeneous component. The magnetic field derived for a sample of very young and compact HFP (Orienti & Dallacasa 2008) has been found in good agreement with the equipartition magnetic field, with values around a few tens of mG.

In the presence of such high magnetic fields, the radiative losses are very severe, making the lifetime of the relativistic electrons responsible for the radio emission very short, and causing a marked cut-off in the optically-thin part of the spectrum. In the case the particle injection stops, the radio spectrum rapidly shifts towards low frequencies becoming undetectable by conventional observations, since only low-energy electrons will be able to survive longer in such high magnetic fields.

It should be noted that in a few source components, the magnetic field computed directly from the observational parameters are very different from the equipartition value. In these cases, the analysis of their radio spectra indicates that the optically-thick regime is too inverted to be due to SSA (see Section 3), and an additional contribution from FFA is needed. This implies that the magnetic field derived from observational parameters is physically meaningless.

3. The ambient medium

The onset of the radio emission is thought to be related to merger or accretion events which feed the central active galactic nucleus (AGN). For this reason, the interstellar medium of galaxies hosting a radio source is rather dense and inhomogeneous. Statistical studies of the atomic hydrogen in absorption of a sample of young radio sources (Pihlström et al. 2003, Gupta et al. 2006) have shown an anti-correlation between the linear size and the HI column density ($N_{\rm HI}$): the larger the source, the smaller the HI column density is. This can be explained assuming that the neutral hydrogen is settled in a circumnuclear torus/disk: the HI absorption is detected against the receding jet when our line of sight passes through the disk/torus along its way toward the radio emission. This interpretation is based on observations with a poor spatial resolution. When pc-scale VLBI observations have been performed, it has been noted that in some compact sources, like 4C 12.50 (Morganti et al. 2004) the HI absorption is not produced by an organized circumnuclear structure, but it probably comes from an unsettled off-nuclear cloud located where the jet bends.

Another evidence of an inhomogeneous medium enshrouding the radio sources arises from the distribution of the ionized medium. VLBI studies of the compact HFP sources OQ 208 (Kameno et al. 2000), J0428+3259, and J1511+0518 (Orienti & Dallacasa 2008) could locate FFA against one lobe only, indicating an asymmetric distribution of the ionized gas. Given their intrinsically small linear size, young radio sources completely reside within such a dense and inhomogeneous environment, where jet-ISM interaction may influence the source evolution. Various work on young radio sources pointed out that in a large number of objects the brightest lobe is also the closest to the core (Saikia et al. 2003, Orienti et al. 2007). Such asymmetries are better interpreted in terms of jet-ISM interaction, instead of projection effects. Furthermore, the detection of HI in absorption only against the brightest (and closest to core) lobe of 3C 49 and 3C 268.3 (Labiano et al. 2006), strongly supports this interpretation. During the time the jet is piercing the cloud, its velocity is considerably slowed down. The interaction prevents adiabatic expansion and the radio luminosity is enhanced by strong radiative losses.

4. High energy emission

Although young radio sources are preferentially studied in the radio band, the knowledge of their high energy emission is crucial in providing us information on the central region of the AGN and on their total energy distribution, i.e. a key element in understanding the source fate.

X-ray detections of GPS/CSSs registered a drastic increase with the advent of *XMM-Newton* and *Chandra* observatories. Observational campaigns on GPS and CSS galaxies (Guainazzi et al. 2006, Vink et al. 2006, Tengstrand et al. 2009) and quasars (Siemiginowska et al. 2008) have been performed for the first time with detection fractions nearly to the 100% on the selected subsamples. However, for most of the cases, the extreme compactness of the sources combined with the spatial resolution of the X-ray observatories ($\sim 1''$ in the best case with *Chandra*) prevents to resolve out the X-ray morphology and locate the site of origin of the high-energy emission. Therefore, the studies rely mainly on the analysis of the X-ray spectral properties (presence of an intrinsic absorber, evaluation of X-ray intrinsic luminosities), but the identification of the various spectral features is often controversial. As a consequence, the origin of the X-ray and high-energy emission remains still a matter of debate. Thermal high energy/X-ray emission is expected from the accretion disk's hot corona or it could arise from interactions between the expanding ra-

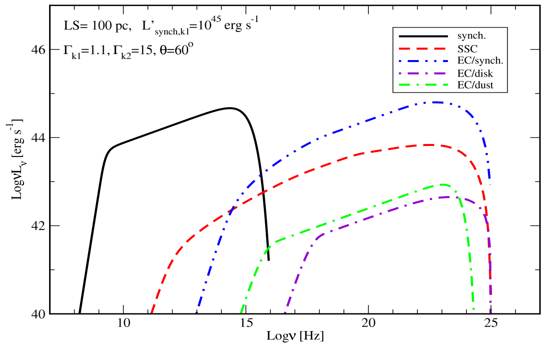

Fig. 1. Modeled SED for a knot located at 100 pc from the core (see text). The different curves show the modeled components: synchrotron emission (synch., *black solid line*), SSC emission (SSC, *red dashed line*), comptonized disc and torus photons (EC/disk and EC/dust *violet dot-dashed line* and *green dot-double dashed line* respectively), and IC emission of external synchrotron photons from a blazar-like component (EC/synch., *blue double-dot-dashed line*).

dio source and the interstellar medium (Reynolds et al. 2001, Bicknell & Sutherland 2006). A significant contribution to the total X-ray flux can be given by the extended components, namely jet, hot spots and lobes, overpressured and powerful at the initial stages. In this case, the mechanism at the basis of high energy emission may be inverse Compton (IC) of either the thermal UV/IR photons from the accretion disk/circumnuclear torus by the lobes' relativistic electrons (Stawarz et al. 2008, Ostorero et al. 2010), or synchrotron photons by a dominant jet component (Migliori et al., in preparation). Lobes' IC emission should be most likely dominant in GPS galaxies, where projection effects should be marginal, while IC emission from jet components is favoured in more powerful GPS and CSS quasars. In the former case, the intensity of the IC emission for a given jet kinetic power, strictly depends on both the lobe size (i.e. its compactness), and the thermal photons arising from the dense and inhomogeneous nuclear ambient medium embedding the radio source. In the latter case, the ingredients at the basis of the high-energy emission are both the velocity of the emitting region, namely a jet knot, and its direction (approaching or moving away) relative to the source of the external thermal/non-thermal photon seeds. We note that while lobes' IC emission is isotropic, the emission from the jet can be strongly beamed. More complexity is added when we consider a jet with a velocity structure, either axial (see e.g. Ghisellini et al. 2005) or radial (Celotti et al. 2001, Georganopoulos & Kazanas 2003), and synchrotron photons of the fast moving component are up-scattered by the electrons in the slower one.

As an example, we show in Figure 1 the results for synchrotron and IC modeled SED for a knot located at 100 pc from the nuclear region, emitting an intrinsic integrated luminosity $L'_{syn.,k1} = 10^{45}$ erg s^{-1}. The expected IC emission produced by the knot electrons with the local synchrotron photons (synchrotron self Compton, SSC), and the external Compton with UV/disc (EC/disc) and IR/torus (EC/torus) photons are calculated. The bolometric disc luminosity is $L'_{disc} = 10^{46}$ erg s^{-1} and about 10% of the disc luminosity is reprocessed in the torus. The knot is moving with a bulk motion $\Gamma_{k1} = 1.1$, and the electron energy distribution is described by a simple power law ($N(\gamma) \propto \gamma^{-p}$) with a energy spectral index $p = 2.6$ and extremes $\gamma_{min} = 10$ and $\gamma_{max} = 10^5$. A second knot, which releases an intrinsic integrated synchrotron luminosity of $L'_{syn.,k2} = 10^{43}$ erg s^{-1}, is located at the jet base and it has a highly relativistic motion ($\Gamma_{k2} = 15$). The synchrotron photons coming from this internal blazar-like component are up-scattered by the electrons in the slow moving outer knot, (EC/synch., see Celotti et al. 2001 for a complete description of the model). The jet axis has an inclination of 60 degrees with respect to the observer line of sight. The dominant contribution to the high energy emission is provided by the EC/synch. emission. Then, the presence of a velocity gradient along the jet seems to play a determinant role in the production of the high energy emission.

4.1. Non-thermal γ-ray emission

An interesting aspect of the non-thermal scenarios, both for lobes in galaxies and jets in quasars, is that compact sources are expected to be also important γ-ray emitters. Observations in the γ-ray band could be important for several aspects:

– they should allow us to discriminate genuinely young/compact sources from projected sources/blazars. In particular, simultaneous, multiwavelength (radio to γ-ray) observations carried out during various epochs, are a powerful tool to catch the elusive variability typical of blazars;

– they should be a decisive confirmation of the non-thermal hypothesis, since high-energy thermal emission is expected to rapidly drop in the MeV-GeV energy bands. Anyway, on this purpose it is worth noting that at the current *Fermi*/LAT sensitivity only the most powerful and near objects may be detected. Certainly this introduces a fundamental bias, especially for the quasar class in average located at relatively high redshifts.

– γ-ray emission from the jet could allow us to shed a light on the jet dynamics during the initial stages, whether there is a single velocity or a more complex structure. In this case, the comparison with the giant counterparts detected by *Fermi*/LAT could

be also important to better understand the general evolutionary path.

5. Conclusions

Intrinsically compact radio galaxies represent a high fraction (15% - 30%) of the sources selected in flux-limited radio catalogues. Their compactness together with their two-sided morphology suggests that their radio emission is still in a young phase and it would likely evolve into the large edge-brightened radio galaxies. This class of objects is characterized by their peaked synchrotron spectrum, likely produced by SSA. Their physical properties indicate that they are in equipartition conditions with typical values of the magnetic fields from a few mG to a few hundred mG in the most compact and brightest components. Such high magnetic fields cause severe energy losses of the relativistic electrons producing thus steep optically-thin spectra. The ambient medium enshrouding these radio sources is quite dense and inhomogeneous, where jet-cloud interaction may take place and influence the source growth, for example impeding the jet expansion.
Although these sources are mainly studied in the radio band, their X-ray emission has been detected with the advent of *Chandra* and *XMM-Newton* observatories. However, the insufficient spatial resolution could not enable us to constrain the site of the X-ray emission, since both thermal and non-thermal models are degenerate in the X-ray band. Non-thermal inverse Compton produced by relativistic electrons from lobes or jets components with either thermal photon seeds from the ambient medium (i.e. disc/torus), or non-thermal synchrotron photons from a relativistic jet knot, may be at the origin of the high-energy emission. *Fermi*/LAT observations in the γ-ray regime will help us in defining the actual region responsible for the high-energy emission, as well as the structure of the newly born radio jets.

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